AN ANALYSIS OF EARTHQUAKE DATA WITH RESPECT TO THE TIDAL FORCE

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THESIS

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WITH RESPECT TO THE TIDAL FORCE

by

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September 1972

An Analysis of Earthquake Data

with Respect to the Tidal Force

by

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from the

NAVAL POSTGRADUATE SCHOOL
September 1972

ABSTRACT

Earthquake data from California from the period of January 1, 1969, to December 31, 1971, has been analyzed by two methods. The first method compares the occurrence of earthquakes with the Synodic, Draconic and Anomalistic Lunar Periods. Statistical tests to determine if the earthquakes are uniformly distributed over each of the three lunar periods are presented. The second method compares three components of the tidal force vector and their derivatives at the times of earthquake occurrences.

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I. INTRODUCTION

A lunar correlation with the time of the occurrence of earthquakes as reported by Allen [Ref. 1] has been one of the methods used in trying to determine the causes of earthquakes for the better part of a century. Knopoff [Ref. 3] reported that it may be that earthquakes have a greater tendency to be triggered when the sun and the moon are nearly aligned with the earth. An interesting observation which was reported by Wigand [Ref. 16] was that the sun and the moon were almost aligned with the earth at the time of the San Fernando Valley Earthquake of February 9, 1971. It is further contended by Wigand [Ref. 16] that there is strong evidence that some earthquakes are related to tidal force, and some are actually triggered by the tidal force. The objective of this thesis was to investigate these findings by analyzing the gravitational forces of the moon and the sun with relation to recorded earthquakes.

Two approaches in analyzing earthquake data are presented. The first approach was to compare the occurrence of earthquakes with the Synodic Lunar Period, the Draconic Lunar Period, and the Anomalistic Lunar Period. The second approach was to investigate the tidal force exerted by the sun and the moon with relation to 155 recorded earthquakes which occurred in the San Fernando Valley from April, 1971, to November, 1971.

The three lunar periods discussed in the first approach are as follows:

1. Synodic Lunar Period, mean value 29.530589 solar days. Defined as new moon to new moon, where the new moon occurs when the geocentric longitudes of the sun and the moon are the same [Ref. 12].
2. Draconic Lunar Period, mean value 27.212220 solar days. Defined as the ascending node to the ascending node, where the ascending node passage of the moon is from minus degrees latitude to positive degrees latitude [Ref. 12].
3. Anomalistic Lunar Period, mean value 27.554531 solar days. Defined as perigee to perigee, where perigee is that point of the moon's orbit at which the moon is nearest to the earth [Ref. 12].

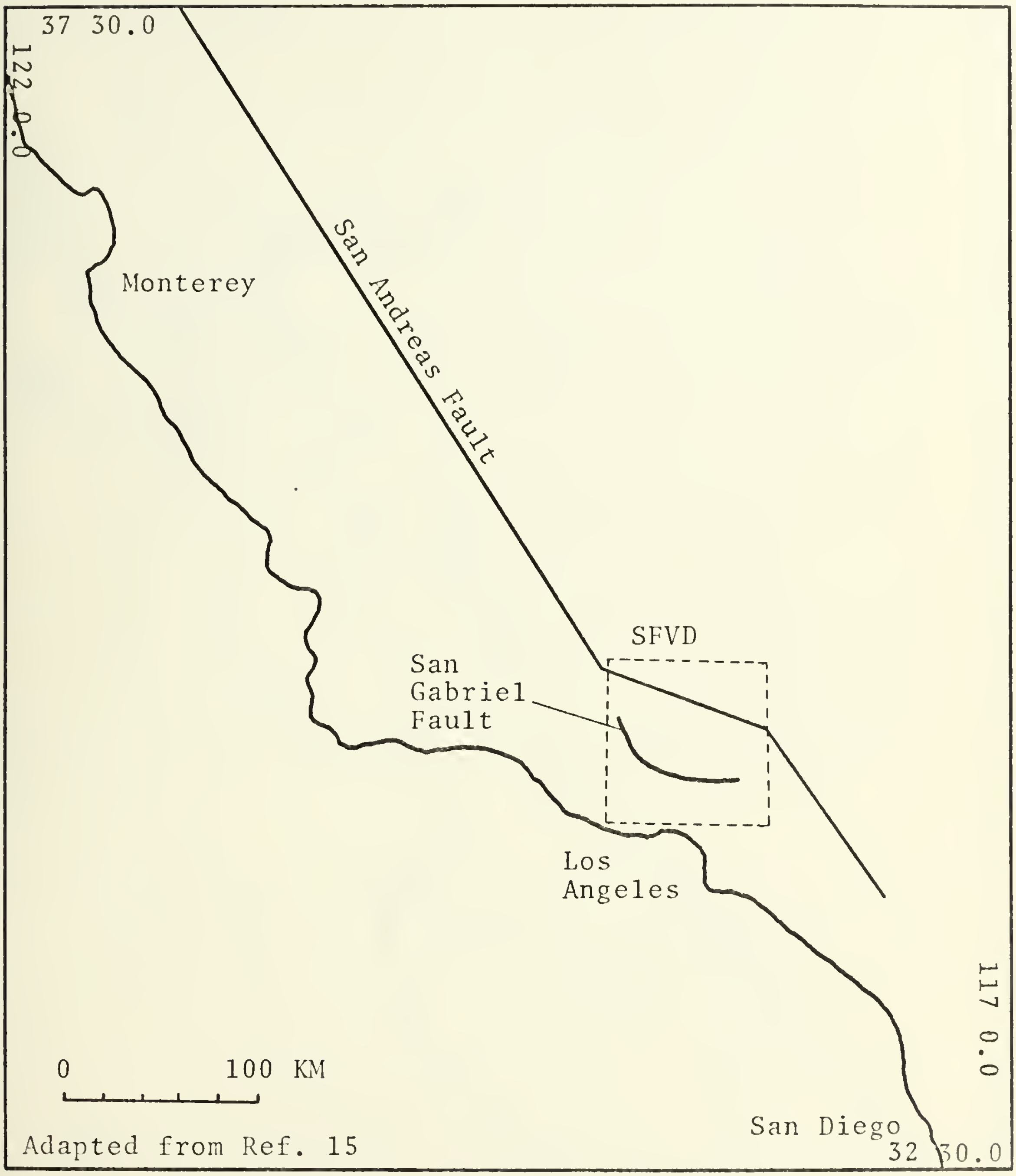
Five lunar periods [Ref. 12] actually exist but the above three were included for the reasons given below. In analyzing the earthquake data with respect to the Synodic Lunar Period, the occurrence of earthquakes with respect to the positions of the sun and the moon are examined. In analyzing the data with respect to the Draconic Lunar Period, the occurrence of earthquakes with respect to the moon's position in the Northern Hemisphere and Southern Hemisphere were examined. This may have been important since the data used included only earthquakes which occurred in California. In analyzing the earthquake data with respect to the Anomalistic Lunar Period, the

difference in the gravitational force of the moon on the earth was examined as the moon proceeded from perigee to apogee to perigee.

The earthquake data received from the National Center for Earthquake Research spanned three time periods and occurred in two areas of California. The first set of data included 155 earthquakes recorded from April 1, 1971, to November 17, 1971. These are classified as aftershocks of the February 9, 1971, San Fernando Valley Earthquake (Figure 1). The magnitudes ranged from 1.0 to 4.2 as measured on the Richter Scale. This set of data will be referred to as the San Fernando Valley Data (SFVD).

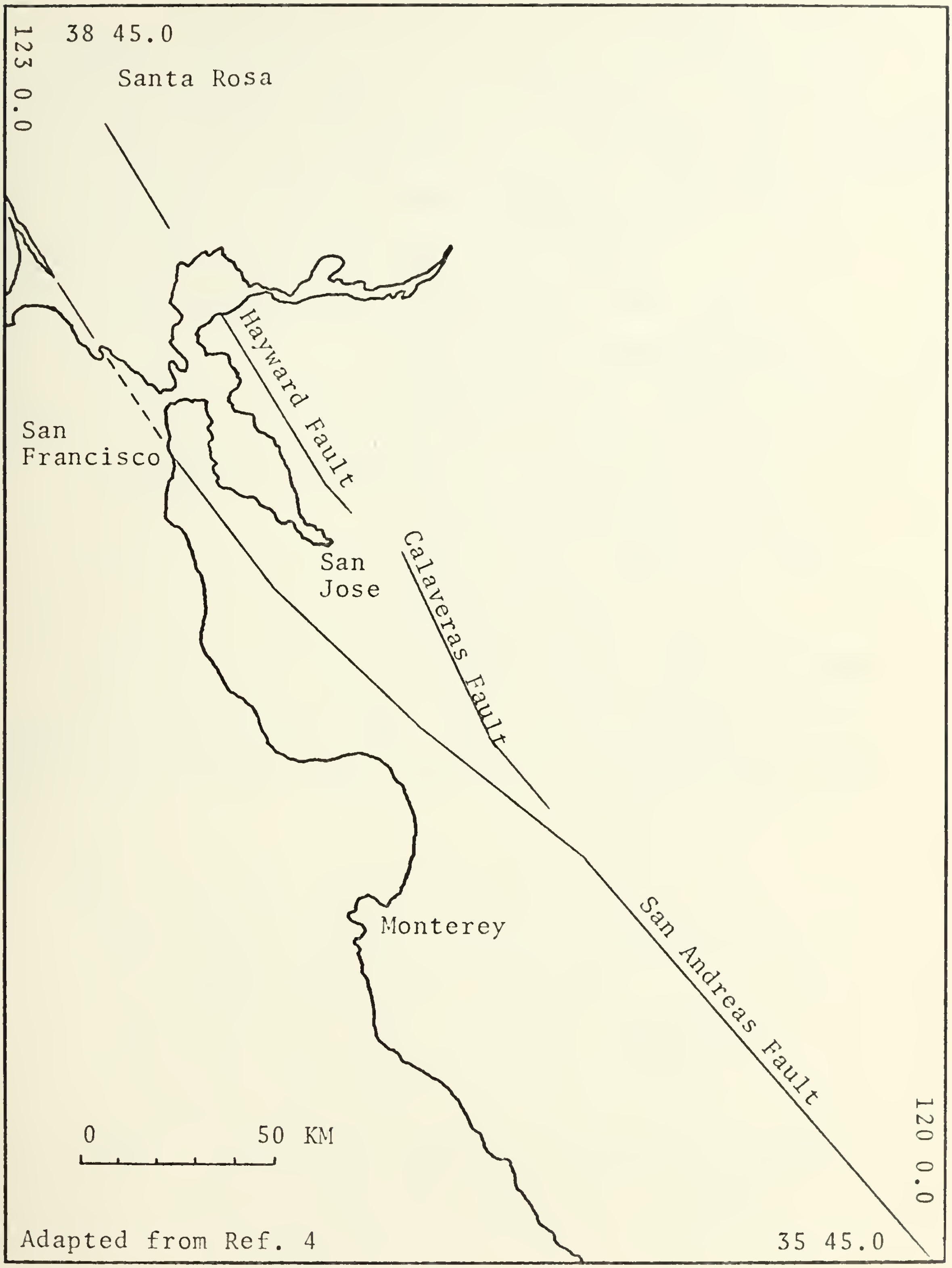
The second set of data included 2879 earthquakes recorded from January 1, 1969, to August 23, 1970. These earthquakes occurred in the San Francisco Bay Area (Figure 2) in the vicinity of the San Andreas Fault, the Hayward Fault, and the Calaveras Fault. The magnitudes ranged from 0.11 to 5.06 as measured on the Richter Scale [Refs. 4 and 5]. This set of data will be referred to as the San Francisco Bay Area Data I (SFBAD-I).

The third set of data included 2734 earthquakes recorded from August 1, 1970, to December 31, 1971. The area was the same as SFBAD-I. The magnitudes ranged from 0.29 to 4.45 as measured on the Richter Scale [Refs. 5 and 6]. This set of data will be referred to as the San Francisco Bay Area Data II (SFBAD-II).



Region (Indicated) of SFVD

FIGURE 1



Region of SFBAD-I and SFBAD-II

FIGURE 2

SFBAD-I and SFBAD-II both included earthquakes which occurred in August, 1970. In the analysis, as discussed in the next section, the duplicate earthquakes were eliminated.

In analyzing the data with respect to the lunar periods, the following hypotheses were investigated:

Null Hypothesis: Earthquakes occur in a uniform distribution with respect to the lunar period.

Alternative Hypothesis: Earthquakes do not occur in a uniform distribution with respect to the lunar period.

Two tests were used in the analysis: The Chi-Square Test for Significance [Ref. 17], and the Goodness of Fit Statistic Vn [Ref. 13]. The tests are discussed in what follows:

The Chi-Square Test for Significance

N, the total number of observations in the samples which were analyzed.

H, the total number of equal intervals in which the lunar period was divided.

$X = \frac{N}{H}$, the expected number of observations which occurred in each interval of a uniform distribution.

Ti, the total number of observations recorded within each interval, i=1,...,H.

df = H - 1, the degrees of freedom associated with the test.

$$\chi^2_{df} = \sum_{j=1}^{H} \frac{(T_j - X)^2}{X}$$, the Chi-Square statistic.

The Goodness of Fit Statistic Vn:

N, the total number of observations in the sample analyzed.

F(x), the uniform distribution on the lunar period in which the origin was the origin of the lunar period.

$F_N(x)$, the distribution of the observations on the lunar period with the same origin as F(x).

X, the time of each earthquake in the sample.

$$Vn = \sup_{-\infty<x<\infty} (F_N(x)-F(x)) - \inf_{-\infty<x<\infty} (F_N(x)-F(x)),$$ the Vn statistic.

Stephens [Ref. 13] stated that if the observations are points on a circle, the value of Vn obtained from the above equation does not depend on the choice of the origin for measuring x. The distribution of Vn refers to the distribution under the null hypothesis [Ref. 13]. Tables of significance of the statistic $\sqrt{N}$ Vn are included in Reference 13.

A simulation of 1000 earthquakes over a period of six months was included in the analysis. The simulation was

performed to test the uniform distribution of the events over the three lunar periods.

The final analysis in this thesis was made possible by the use of a computer program by Professor Rex H. Shudde of the Naval Postgraduate School. This computer program calculated three components of the tidal force (measured in microgals) at the epicenter of an earthquake.

The three components are the radial component, the north component, and the east component. The radial component of the tidal force vector is through the center of the earth and the epicenter of the earthquake. The north and east components of the tidal force vector are in the plane which passes through the epicenter and is perpendicular to the radial component. The computer program also calculated the rates of change of the three components described above. The three components were plotted for a 24-hour time period on the day each earthquake occurred. A visual comparison of the plots of the 155 earthquakes which occurred in the San Fernando Valley with respect to the three components of the tidal force was made. The results of the comparison are in Section III.

II. ANALYSIS AND DISCUSSION OF THE LUNAR PERIOD COMPUTER PROGRAM

The computer program used to analyze the frequency of earthquake occurrences during the Synodic, Draconic and Anomalistic Lunar Periods contains the following steps. The first step involves the time frame of the three sets of data and the lengths of the lunar periods within these time frames. The mean times of the three lunar periods, as given in the Introduction, were not used in the program, since the actual lengths of the periods vary considerably. An example of this difference was the Anomalistic Month which has a mean period of 27.32166 days. During 1971 the length of the Anomalistic Month ranged from 25.41667 days to 28.45833 days [Ref. 9].

The times of new moon and lunar perigee for the years 1969, 1970 and 1971 are tabulated in References 7, 8 and 9. From these times (to be referred to as origins) the different period lengths of the Synodic and Anomalistic onths were computed. References 7, 8 and 9 also include tables indicating the apparent latitude of the moon for the respective years at intervals of one half day. The origins for the Draconic Month, as the moon passed from the Southern Hemisphere to the Northern Hemisphere, were computed from these tables by linear interpolation. This procedure should be fairly accurate since it involves only minutes and seconds of latitude.

The origins of the three lunar periods and the times of each earthquake occurrence were put into the program in year, month, day, hours, minutes and seconds in Greenwich Mean Time (GMT). Within the program the year, month and day of each event were converted to the respective Julian Day Number (JD) [Ref. 14]. The hours, minutes and seconds constituted a fraction (Fract) of a day. The Julian Date was computed as follows:

$$\text{Julian Date} = \text{JD} + \text{Fract} - 0.50$$

The one half day was subtracted due to the differences in origins of the Julian Day Number and GMT. The Julian Day Number had its origin at noon whereas GMT has its origin at midnight.

In order to simplify the statistical tests which followed in the program, the data was truncated to insure that no fractions of a period were included. An example of this was the SFBAD-I and the Synodic Month. The time the SFBAD-I started was January 1, 1969, which was between the two new moons of December 19, 1968, and January 18, 1969. Since the events that may have occurred from December 19, 1968, to December 31, 1968, were not included, the events from January 1, 1969, to January 18, 1969, were excluded in the analysis. Similarly fractions of periods were eliminated for the Draconic and Anomalistic Months.

Each of the three lunar time periods was reduced to the unit circle as explained in the following example. The

length of the Synodic Lunar Period from April 25, 1971, to May 24, 1971, was 29.354170 days. At the time of the new moon on April 25, the value on the unit circle was zero. At the time of the first quarter moon on May 2, the value on the unit circle was 0.25. At the time of the full moon on May 9, the value on the unit circle was 0.50. At the time of the third quarter moon on May 17, the value on the unit circle was 0.75. Finally at the time of the new moon on May 24, the value on the unit circle was 1.0 [Ref. 9].

The time at which each earthquake occurred during the lunar period (residual) was placed upon the unit circle with respect to the respective origins. This was accomplished by dividing the difference between the Julian Date of the earthquake and the Julian Date of the origin immediately preceding the earthquake by the length of the period in which the earthquake occurred.

The unit circle was divided into 20 equal intervals in order to perform the Chi-Square Test for Significance [Ref. 17] as explained in the Introduction. Ostle [Ref. 10] suggests, as a rule of thumb, to use no fewer than three for the expected frequency in each interval. Ostle [Ref. 10] further contends that if some expected numbers are too small the Chi-Square statistic will be a poor indicator of the validity of the hypothesis under test. By selecting 20 intervals, the earthquakes in the three sets of data comply with the rule of thumb for expected frequencies.

The residuals that were computed were then sorted into ascending order [Ref. 2] so that the Vn Goodness of Fit Test could be computed as explained in the Introduction. The Vn Goodness of Fit Test is a modification of the Kolmogorov-Smirnov Test [Ref. 13] which is considered to be generally a more powerful test than the Chi-Square Test [Ref. 10].

The output of the program consisted of the total number of events that occurred during each of the three lunar periods; the number of events and the percentages which occurred within each of the 20 intervals, the Chi-Square statistic, and the Vn and $\sqrt{N}$ Vn statistics.

III. RESULTS

The simulation of the 1000 earthquakes as stated in the Introduction was performed to test the uniform distribution of the events on the three lunar periods. The null hypothesis that the simulated earthquakes were distributed uniformly was accepted for each of the lunar periods. The bases for the acceptances were the Chi-Square Test with 19 degrees of freedom and the Vn Test. The Chi-Square statistics and the $\sqrt{N}$ Vn statistics calculated are given below:

	Synodic	Draconic	Anomalistic
Chi-Square	23.28	22.04	28.96
$\sqrt{N}$ Vn	1.4002	1.2130	1.3995

The null hypothesis and alternative hypothesis are:

Null Hypothesis: Earthquakes occur in a uniform distribution with respect to the lunar period.

Alternative Hypothesis: Earthquakes do not occur in a uniform distribution with respect to the lunar period.

If the null hypothesis is accepted, it might imply that the moon's gravitational effects on the earth do not trigger earthquakes. Conversely if the null hypothesis is rejected and the alternative hypothesis is accepted then it might imply that the moon's gravitational effects on the earth do trigger earthquakes.

The results of the statistical tests performed on the three sets of data with respect to the Synodic, Draconic and Anomalistic Lunar Periods are presented in tables. Results suggested by the tidal force plots are discussed following the tables.

In each table the following definitions are used:

Mag - Magnitudes of earthquakes greater than or equal to the magnitude entered in the table.

No - Number of earthquakes in the sample.

Chi - The Chi-Square statistic with 19 degrees of freedom.

a - The one per cent significance level for the Chi-Square statistic [Ref. 11].

Vn - The Vn statistic.

$Vn\sqrt{N}$ - The Vn statistic for large values of No.

b - The one per cent significance level for the Vn statistic.

Acc - Acceptance of the null hypothesis at the one per cent significance level.

Rej - Rejection of the null hypothesis at the one per cent significance level.

Polar plots of the occurrence of earthquakes during the lunar periods are presented in Figures 3, 4, 5, 6, 7, 8, 9, 10, and 11.

A. SAN FERNANDO VALLEY

1. Synodic Month

Mag	No	Chi	a	Vn	Vn$\sqrt{N}$	b
All	110	43.818	REJ	.18258	1.91496	ACC
$\geq$ 1.75	106	33.245	ACC	.15788	1.62552	ACC
$\geq$ 2.00	104	34.077	ACC	.15444	1.57496	ACC
$\geq$ 2.25	96	38.167	REJ	.14963	1.46607	ACC
$\geq$ 2.50	88	28.364	ACC	.14395	1.35035	ACC

Table 1

2. Draconic Month

Mag	No	Chi	a	Vn	Vn$\sqrt{N}$	b
$\geq$ All	119	34.109	ACC	.16705	1.82225	ACC
$\geq$ 1.75	115	26.739	ACC	.14775	1.58449	ACC
$\geq$ 2.00	112	25.857	ACC	.14285	1.51158	ACC
$\geq$ 2.25	103	28.068	ACC	.14267	1.44793	ACC
$\geq$ 2.50	93	26.355	ACC	.14475	1.39593	ACC

Table 2

3. Anomalistic Month

Mag	No	Chi	a	Vn	Vn$\sqrt{N}$	b
All	122	21.934	ACC	.15824	1.74781	ACC
$\geq$ 1.75	118	19.627	ACC	.14189	1.54135	ACC
$\geq$ 2.00	115	20.478	ACC	.13843	1.48455	ACC
$\geq$ 2.25	104	21.000	ACC	.14804	1.50976	ACC
$\geq$ 2.50	93	19.903	ACC	.14287	1.37782	ACC

Table 3

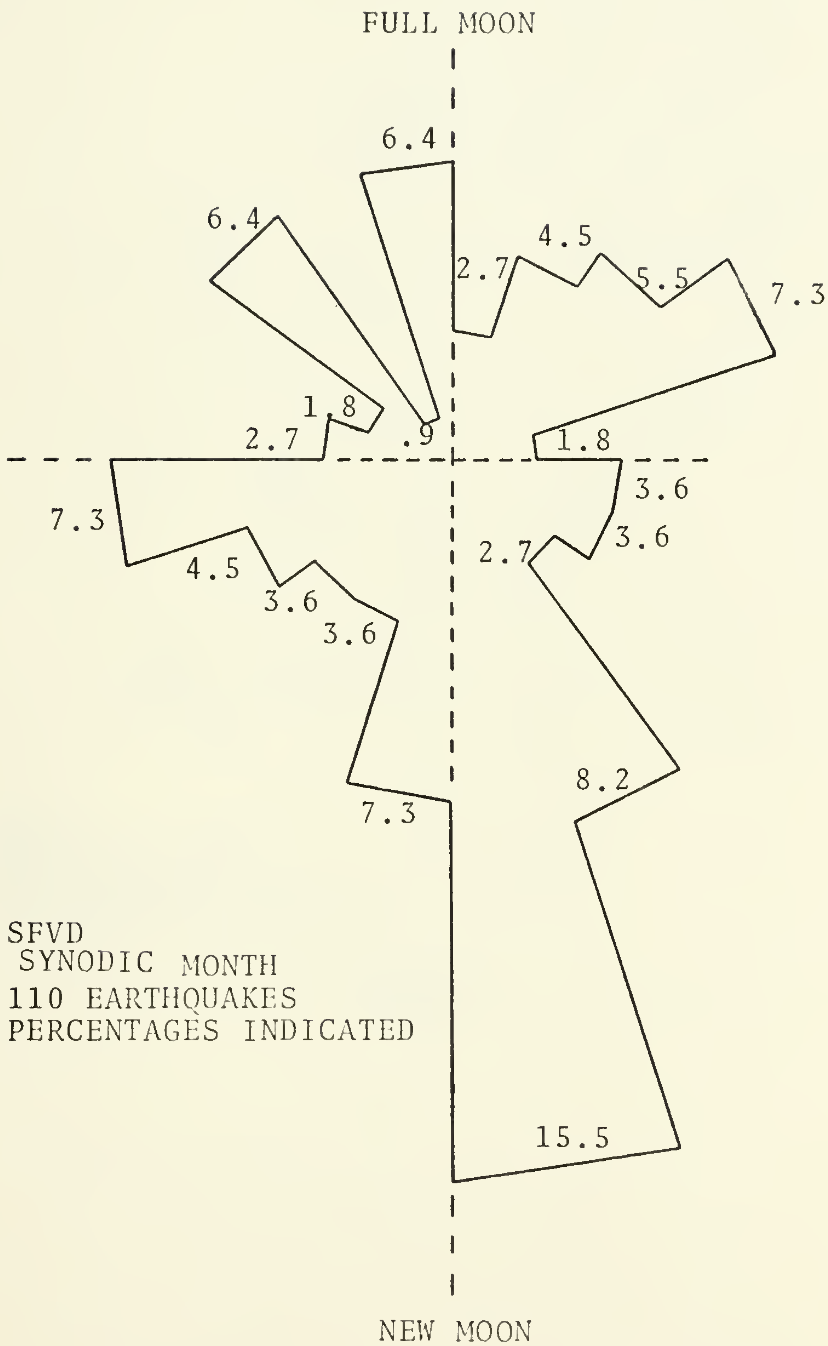

FULL MOON
6.4
6.4
2.7
4.5
5.5
7.3
1.8
2.7
.9
1.8
3.6
7.3
3.6
2.7
4.5
3.6
3.6
8.2
7.3
SFVD
SYNODIC MONTH
110 EARTHQUAKES
PERCENTAGES INDICATED
15.5
NEW MOON

FIGURE 3

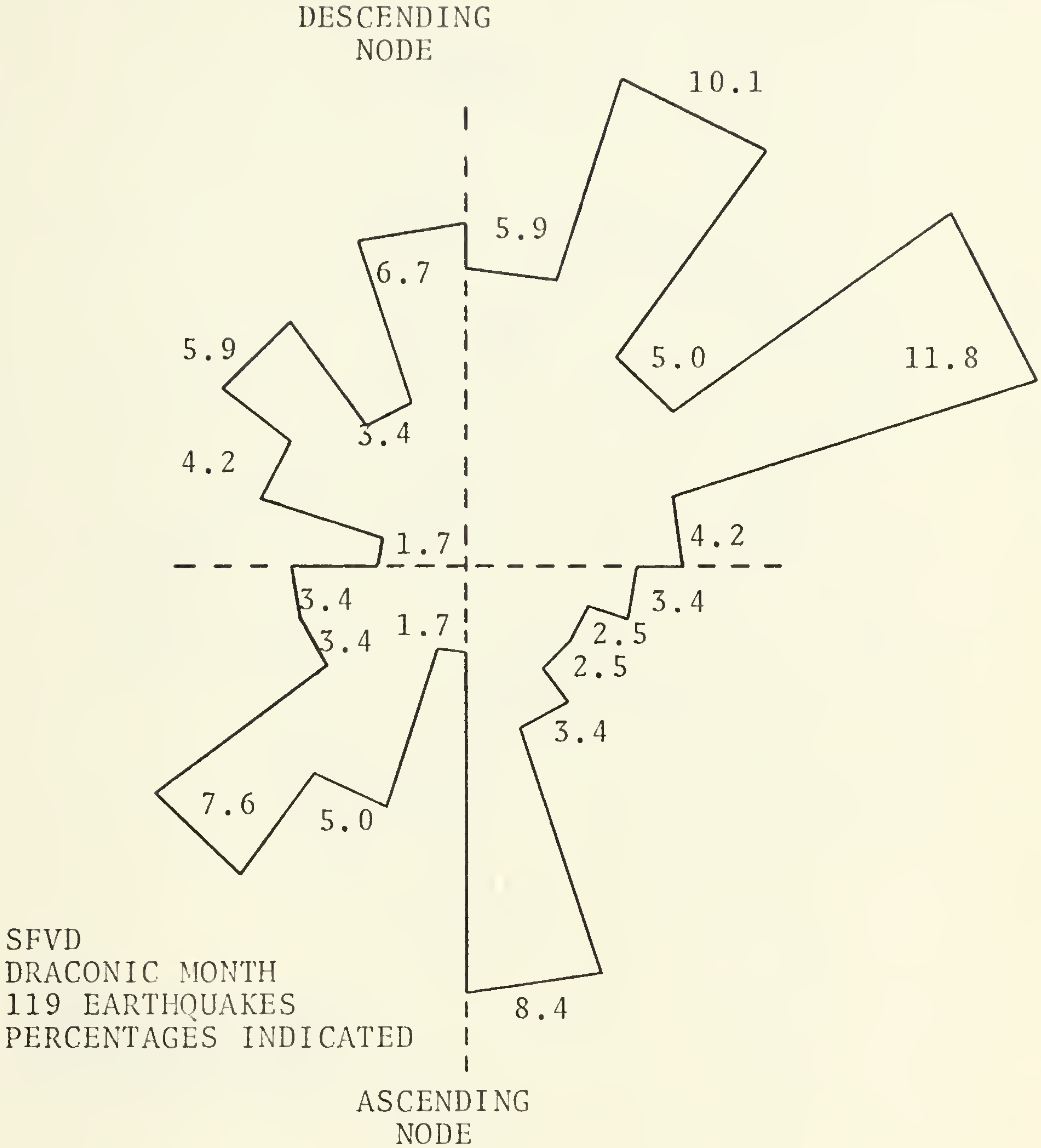
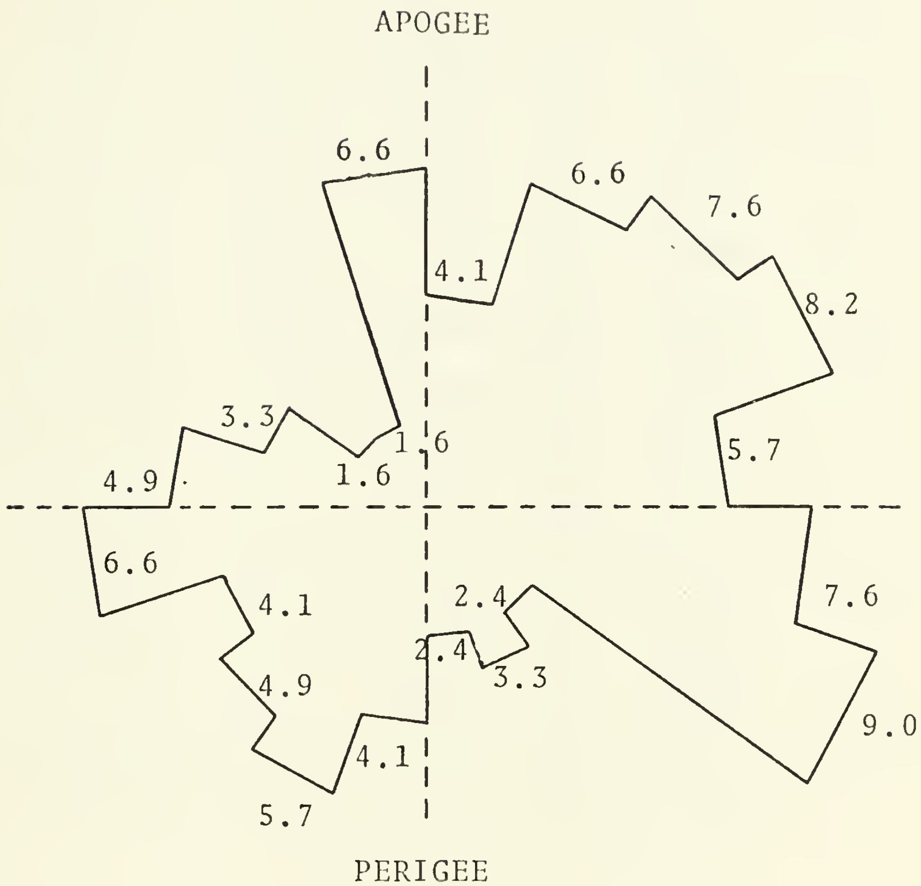

DESCENDING
NODE
10.1
5.9
6.7
5.9
5.0
11.8
3.4
4.2
1.7
4.2
3.4
3.4
1.7
3.4
2.5
2.5
3.4
7.6
5.0
SFVD
DRACONIC MONTH
119 EARTHQUAKES
PERCENTAGES INDICATED
8.4
ASCENDING
NODE

FIGURE 4



SFVD
ANOMALISTIC MONTH
122 EARTHQUAKES
PERCENTAGES INDICATED

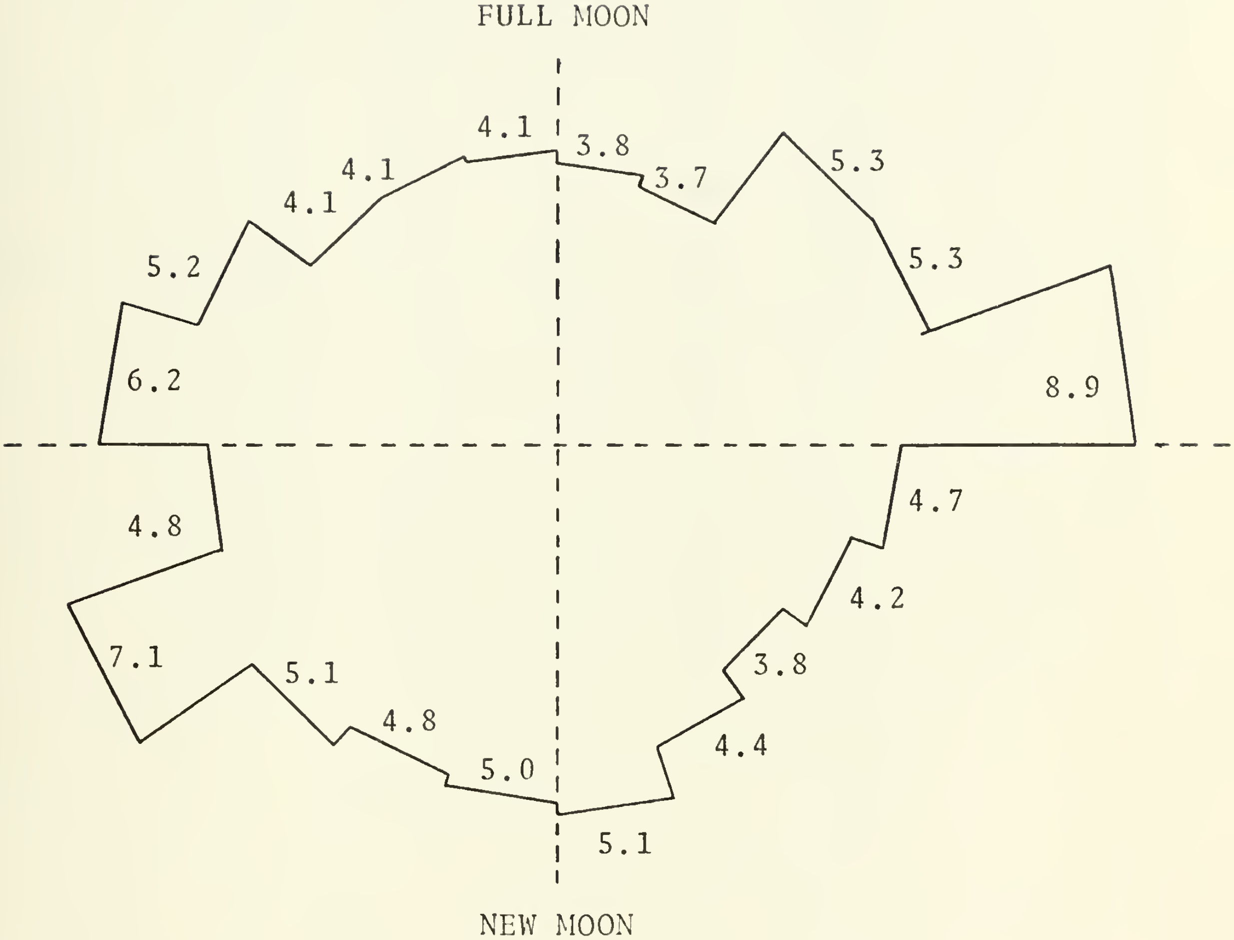
FIGURE 5

B. SAN FRANCISCO BAY EARTHQUAKE DATA I

1. Synodic Month

Mag	No	Chi	a	Vn	$Vn\sqrt{N}$	b
All	2721	156.405	REJ	.05351	2.79130	REJ
$\geq$ 0.50	2554	171.090	REJ	.05848	2.95563	REJ
$\geq$ 0.75	2333	187.660	REJ	.06551	3.16441	REJ
$\geq$ 1.00	2008	202.358	REJ	.06693	2.99933	REJ
$\geq$ 1.25	1580	204.278	REJ	.07694	3.03841	REJ
$\geq$ 1.50	1193	186.966	REJ	.08954	3.09260	REJ
$\geq$ 1.75	803	170.425	REJ	.09327	2.64308	REJ
$\geq$ 2.00	483	106.772	REJ	.09356	2.05609	REJ
$\geq$ 2.25	301	93.485	REJ	.11281	1.95726	ACC
$\geq$ 2.50	177	125.034	REJ	.16622	2.21147	REJ
$\geq$ 2.75	111	98.189	REJ	.18296	1.92756	ACC
$\geq$ 3.00	64	83.500	REJ	.24541	1.96325	REJ

Table 4



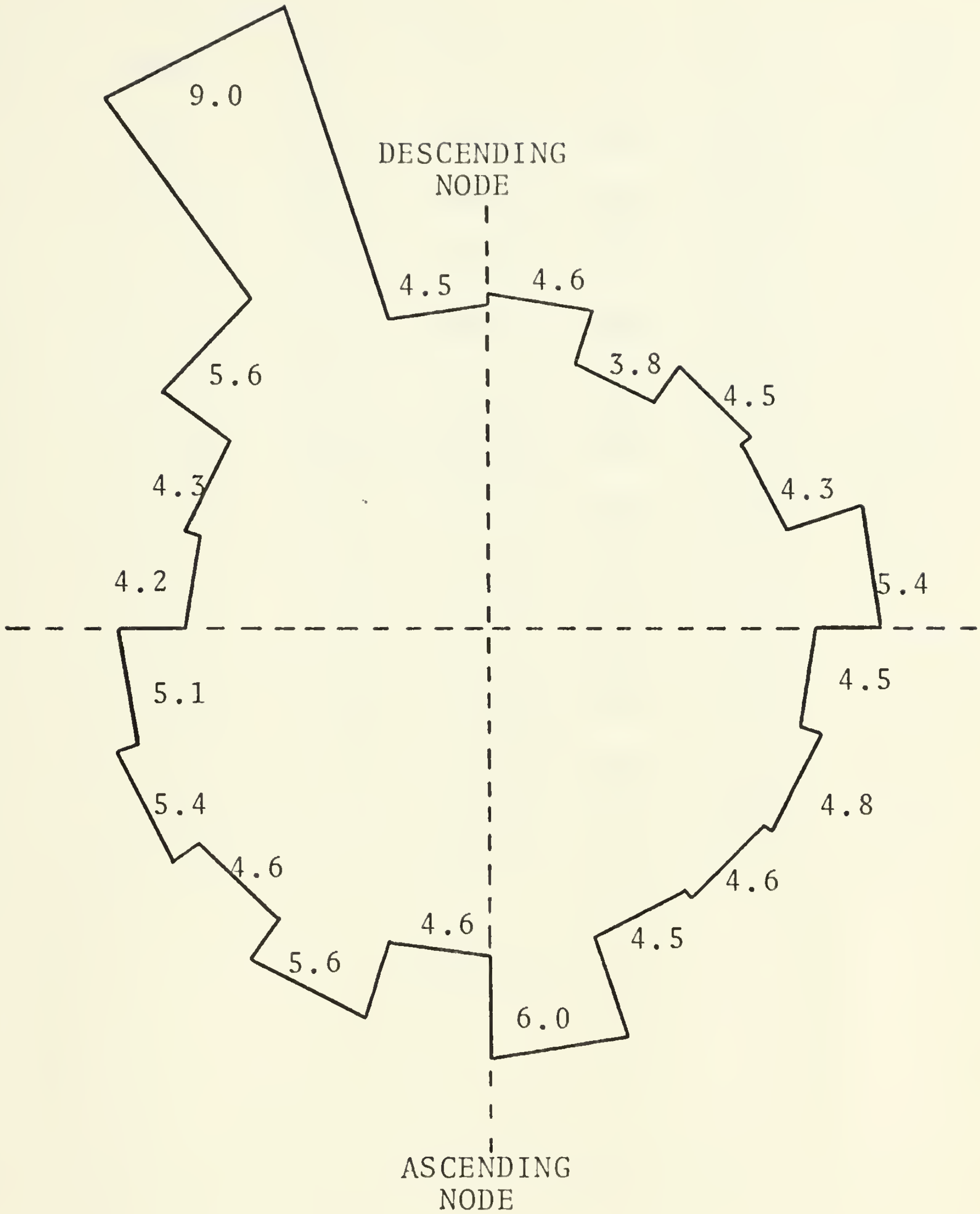
SFBAD-I
SYNODIC MONTH
2721 EARTHQUAKES
PERCENTAGES INDICATED

FIGURE 6

2. Draconic Month

Mag	No	Chi	a	Vn	$Vn\sqrt{N}$	b
All	2780	127.611	REJ	.04939	2.60438	REJ
$\geq$ 0.50	2611	141.823	REJ	.04908	2.50802	REJ
$\geq$ 0.75	2384	162.342	REJ	.05230	2.55383	REJ
$\geq$ 1.00	2048	163.230	REJ	.06090	2.75592	REJ
$\geq$ 1.25	1611	180.521	REJ	.06805	2.73115	REJ
$\geq$ 1.50	1214	148.965	REJ	.07410	2.58155	REJ
$\geq$ 1.75	818	115.203	REJ	.08995	2.57271	REJ
$\geq$ 2.00	493	65.823	REJ	.09078	2.01568	REJ
$\geq$ 2.25	310	48.193	REJ	.11873	2.09050	REJ
$\geq$ 2.50	184	70.348	REJ	.14956	2.02866	REJ
$\geq$ 2.75	116	58.138	REJ	.13858	1.49258	ACC
$\geq$ 3.00	66	45.515	REJ	.14618	1.18757	ACC

Table 5



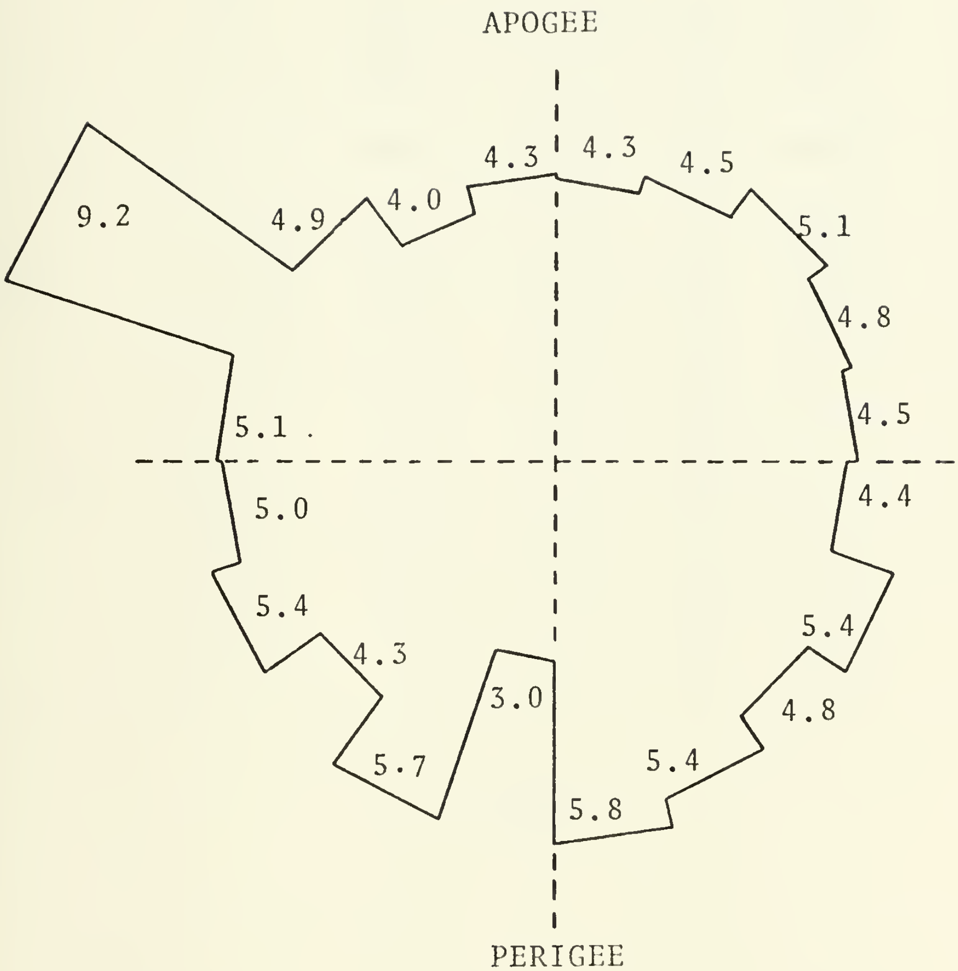
SFBAD-I
DRACONIC MONTH
2760 EARTHQUAKES
PERCENTAGES INDICATED

FIGURE 7

3. Anomalistic Month

Mag	No	Chi	a	Vn	Vn$\sqrt{N}$	b
All	2794	148.190	REJ	.05336	2.82060	REJ
$\geq$ 0.50	2625	144.379	REJ	.05320	2.72548	REJ
$\geq$ 0.75	2398	153.409	REJ	.05437	2.66237	REJ
$\geq$ 1.00	2061	156.613	REJ	.06303	2.86128	REJ
$\geq$ 1.25	1623	142.878	REJ	.06268	2.52532	REJ
$\geq$ 1.50	1224	115.314	REJ	.07092	2.48117	REJ
$\geq$ 1.75	822	94.448	REJ	.08887	2.54783	REJ
$\geq$ 2.00	496	51.823	REJ	.09322	2.07606	REJ
$\geq$ 2.25	310	40.710	REJ	.10603	1.86686	ACC
$\geq$ 2.50	184	38.826	REJ	.12593	1.70822	ACC
$\geq$ 2.75	116	34.345	ACC	.17119	1.84375	ACC
$\geq$ 3.00	66	26.727	ACC	.14634	1.18887	ACC

Table 6



SFBAD-I
ANOMALISTIC MONTH
2794 EARTHQUAKES
PERCENTAGES INDICATED

FIGURE 8

C. SAN FRANCISCO BAY EARTHQUAKE DATA II

1. Synodic Month

Mag	No	Chi	a	Vn	$Vn\sqrt{N}$	b
All	2595	135.767	REJ	.06405	3.26256	REJ
$\geq$ 0.50	2571	132.034	REJ	.06204	3.14580	REJ
$\geq$ 0.75	2438	132.336	REJ	.06392	3.15630	REJ
$\geq$ 1.00	2144	122.847	REJ	.06422	2.97360	REJ
$\geq$ 1.25	1691	96.002	REJ	.06416	2.63846	REJ
$\geq$ 1.50	1228	78.384	REJ	.07451	2.61101	REJ
$\geq$ 1.75	810	65.506	REJ	.08914	2.53705	REJ
$\geq$ 2.00	459	47.710	REJ	.11265	2.41349	REJ
$\geq$ 2.25	275	35.764	ACC	.11716	1.94280	ACC
$\geq$ 2.50	155	33.774	ACC	.14005	1.74338	ACC
$\geq$ 2.75	79	27.076	ACC	.18849	1.67538	ACC

Table 7

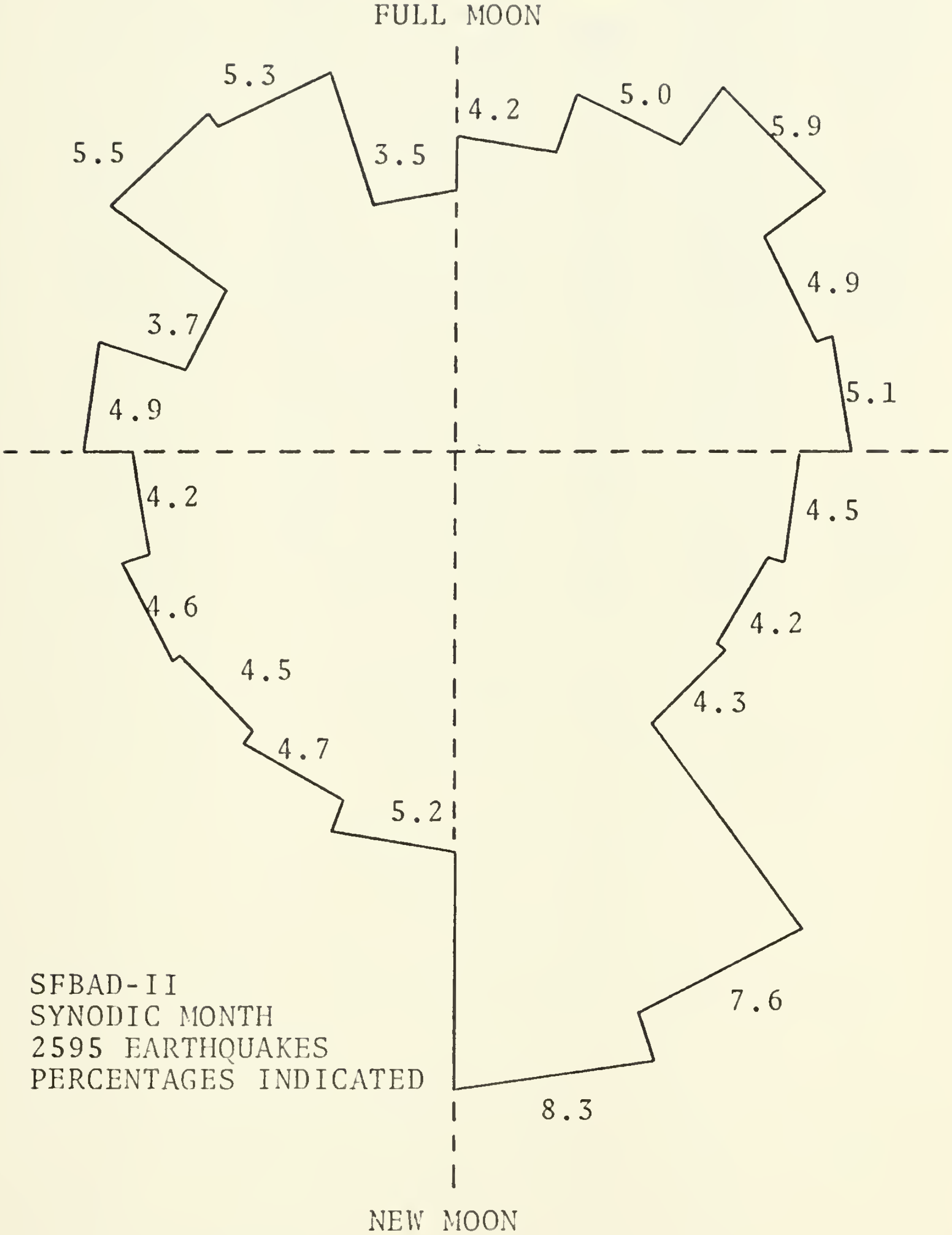
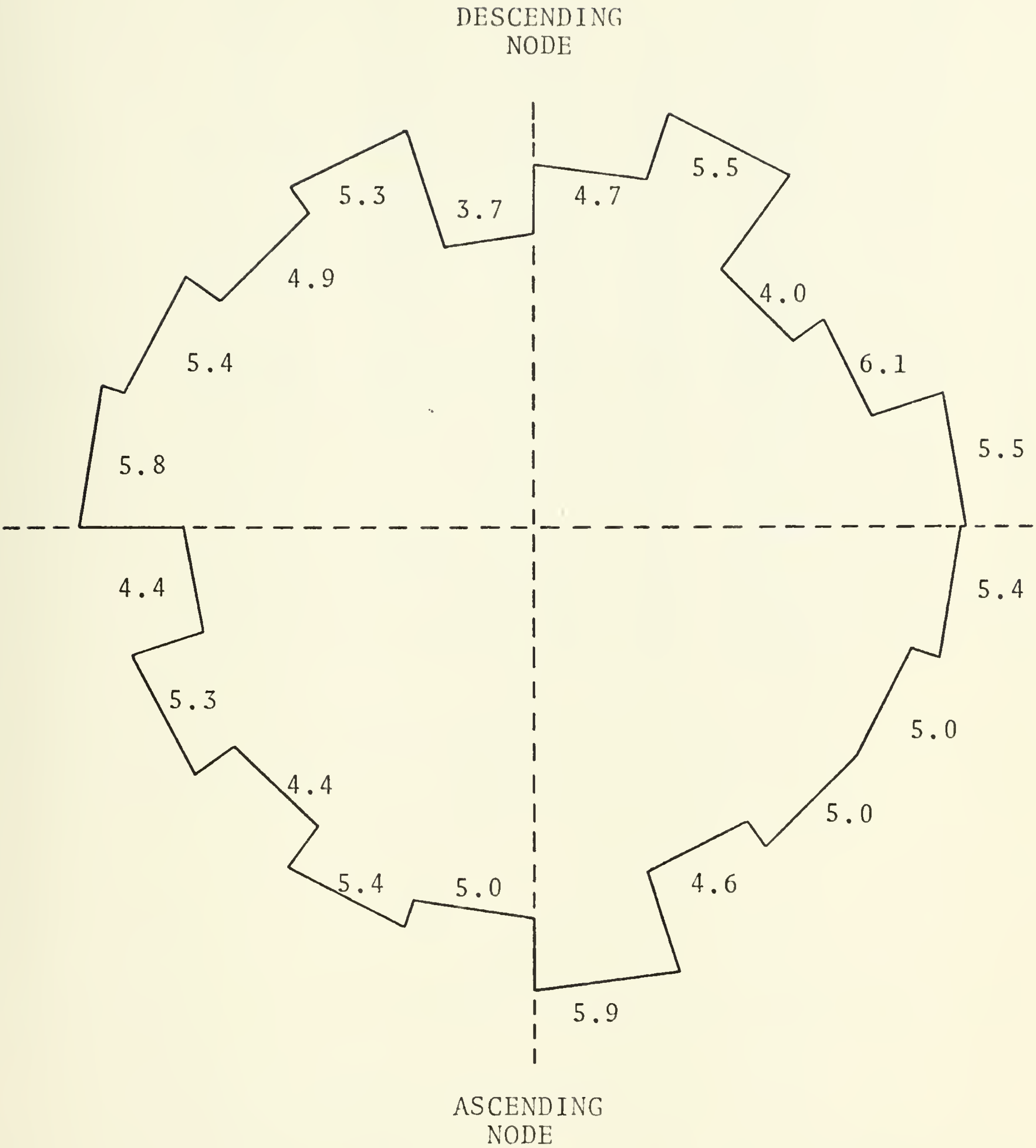

FULL MOON
5.3
5.5
4.2
5.0
5.9
3.5
4.9
3.7
4.9
5.1
4.2
4.5
4.6
4.2
4.5
4.3
4.7
5.2
SFBAD-II
SYNODIC MONTH
2595 EARTHQUAKES
PERCENTAGES INDICATED
7.6
8.3
NEW MOON

FIGURE 9

2. Draconic Month

Mag	No	Chi	a	Vn	Vn$\sqrt{N}$	b
All	2556	31.512	ACC	.03189	1.61201	ACC
$\geq$ 0.50	2534	32.140	ACC	.03155	1.58830	ACC
$\geq$ 0.75	2406	31.506	ACC	.03599	1.76540	ACC
$\geq$ 1.00	2117	23.680	ACC	.03257	1.49860	ACC
$\geq$ 1.25	1668	17.875	ACC	.03807	1.55467	ACC
$\geq$ 1.50	1212	25.294	ACC	.05430	1.89038	ACC
$\geq$ 1.75	810	18.151	ACC	.05296	1.49892	ACC
$\geq$ 2.00	454	26.529	ACC	.06228	1.32712	ACC
$\geq$ 2.25	271	26.491	ACC	.07411	1.22006	ACC
$\geq$ 2.50	152	31.158	ACC	.09405	1.15959	ACC
$\geq$ 2.75	77	25.597	ACC	.13345	1.17102	ACC

Table 8



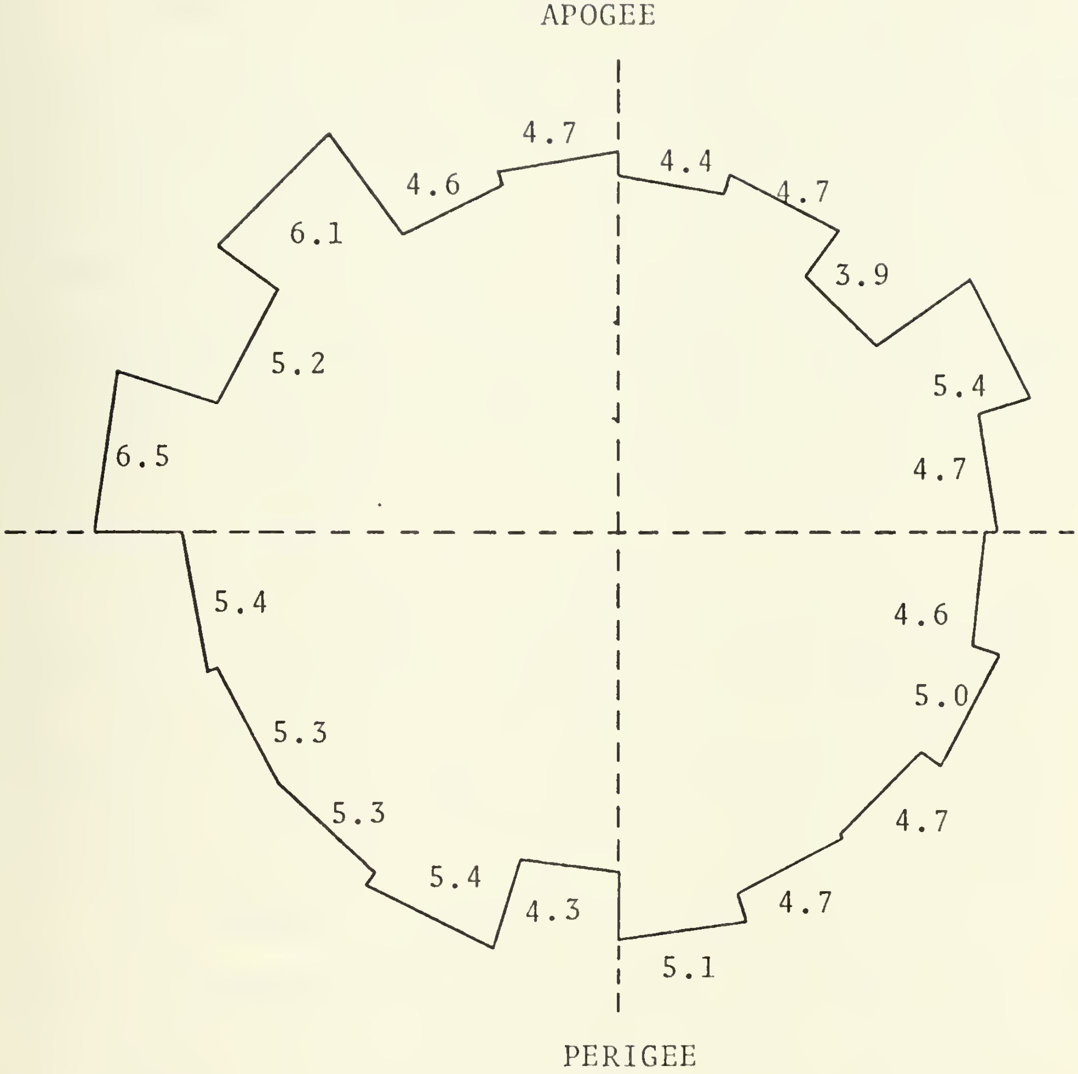
SFBAD-II
DRACONIC MONTH
2556 EARTHQUAKES
PERCENTAGES INDICATED

FIGURE 10

3. Anomalistic Month

Mag	No	Chi	a	Vn	$Vn\sqrt{N}$	b
All	2634	36.752	REJ	.04930	2.53041	REJ
≥ 0.50	2611	35.181	ACC	.04856	2.48153	REJ
≥ 0.75	2479	40.943	REJ	.05378	2.67761	REJ
≥ 1.00	2184	45.982	REJ	.05309	2.48120	REJ
≥ 1.25	1717	43.641	REJ	.05110	2.11722	REJ
≥ 1.50	1251	48.265	REJ	.06704	2.37127	REJ
≥ 1.75	829	49.673	REJ	.07730	2.22563	REJ
≥ 2.00	473	36.302	REJ	.09228	2.00702	REJ
≥ 2.25	286	31.203	ACC	.10886	1.84091	ACC
≥ 2.50	162	32.321	ACC	.11470	1.45990	ACC
≥ 2.75	84	31.238	ACC	.14562	1.33464	ACC

Table 9



SFBAD-II
ANOMALISTIC MONTH
2634 EARTHQUAKES
PERCENTAGES INDICATED

FIGURE 11

D. TIDAL FORCE COMPONENTS WITH RESPECT TO THE SAN FERNANDO VALLEY DATA

Figure 12 is an illustration of the tidal force plots used in the analysis. The occurrence of the earthquake in the plot was May 19, 1971 at 0451 GMT. The magnitude of the earthquake was 2.6. The radial component of the tidal force, as measured in microgals, was positive and decreasing in value (negative slope). The north component was negative and increasing in value (positive slope). The east component was negative and decreasing in value (negative slope).

The same 110 SFVD earthquakes which were analyzed with respect to the Synodic Lunar Period were investigated as the event presented above. The results are tabulated in Table 10. The time frame in which these earthquakes occurred was from April 25, 1971, to October 19, 1971.

Ten thousand earthquakes uniformly distributed in time were simulated during the previously mentioned time frame and in the same area as the SFVD. These simulated earthquakes were analyzed in the same manner. The results are also tabulated in Table 10.

Each component at the time of the earthquake was either positive or negative in value. The derivatives of each of the three components was either positive or negative at the time of the earthquake. Sixty-four combinations of the three components and their slopes were then considered. In Table 10 the following definitions are used.

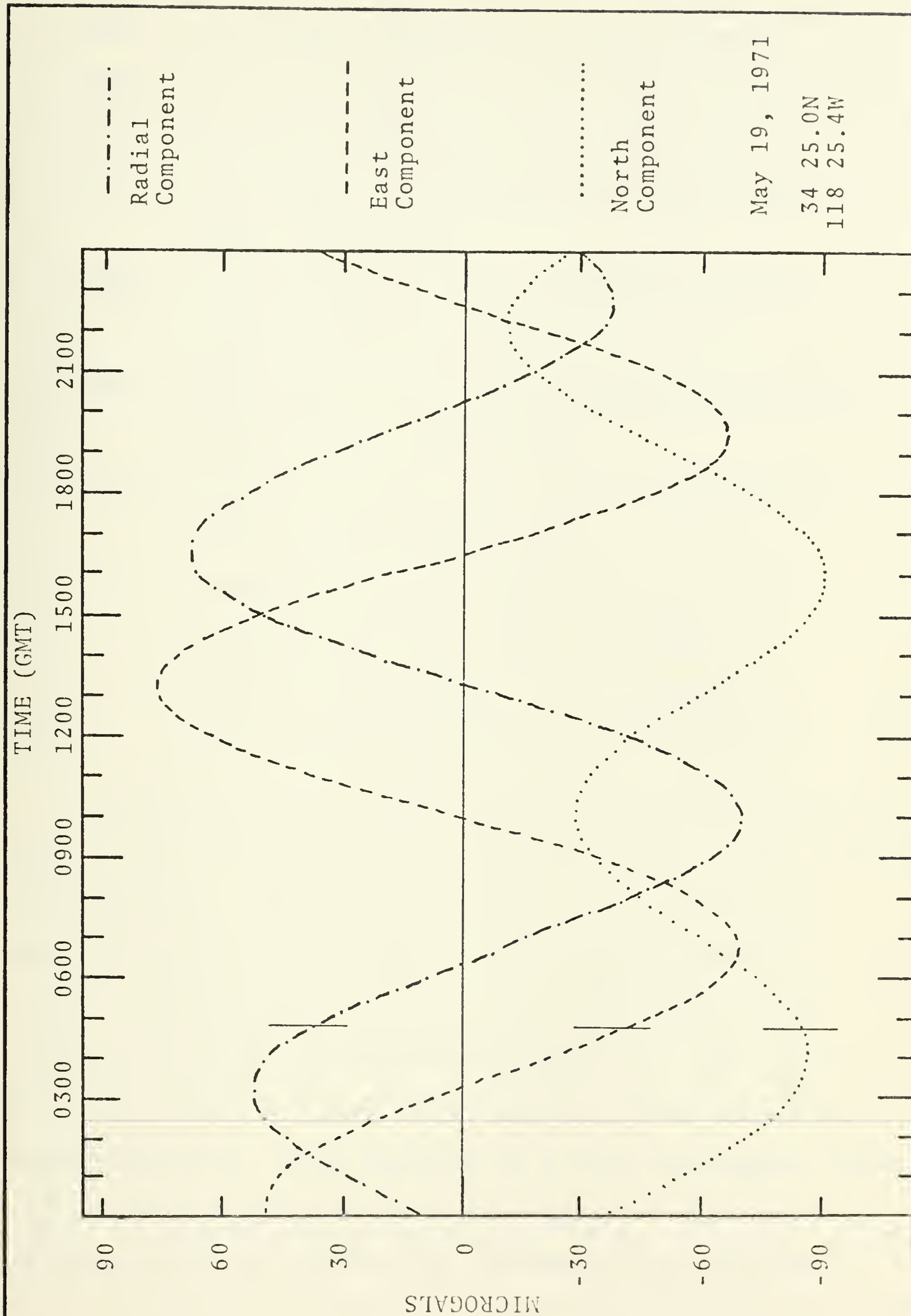

Radial Component
East Component
North Component
May 19, 1971
34 25.0N
118 25.4W
TIME (GMT)
0300
0600
0900
1200
1500
1800
2100
90
60
30
0
-30
-60
-90
MICROGALS

FIGURE 12

RAD - The radial component of the tidal force.

NOR - The north component of the tidal force.

EAS - The east component of the tidal force.

REC - The number of earthquakes recorded with the same combination.

PREC - The percentage of the earthquakes recorded with the same combination.

SIM - The number of simulated earthquakes recorded with the same combination.

PSIM - The percentage of the simulated earthquakes with the same combination.

+ - Component of tidal force was positive.

\- - Component of tidal force was negative.

p - Value of the component was increasing.

n - Value of the component was decreasing.

The data in Table 10 were used to compare the distribution of the earthquakes with the distribution of the simulated earthquakes by means of a Contingency Table [Ref. 10]. The null hypothesis was that the two distributions are the same. The combinations of the three components of the tidal force vector and the three derivatives, for which the actual and the simulated earthquakes never occurred, were eliminated. This resulted in a 2X34 Contingency Table. The Chi-Square statistic with 33 degrees of freedom was computed (39.972) and the null hypothesis was accepted.

RAD	NOR	EAS	REC	PREC	SIM	PSIM
+p	+p	+p	0	0	0	0
-p	+p	+p	5	4.55	206	2.06
+n	+p	+p	0	0	0	0
-n	+p	+p	0	0	0	0
+p	-p	+p	0	0	21	.21
-p	-p	+p	4	3.64	469	4.69
+n	-p	+p	0	0	0	0
-n	-p	+p	0	0	1	.01
+p	+n	+p	0	0	74	.74
-p	+n	+p	3	2.73	179	1.79
+n	+n	+p	0	0	0	0
-n	+n	+p	0	0	0	0
+p	-n	+p	1	.91	215	2.15
-p	-n	+p	9	8.18	1350	13.50
+n	-n	+p	0	0	0	0
-n	-n	+p	0	0	6	.06
+p	+p	-p	0	0	0	0
-p	+p	-p	0	0	0	0
+n	+p	-p	1	.91	69	.69
-n	+p	-p	5	4.55	161	1.61
+p	-p	-p	0	0	0	0
-p	-p	-p	0	0	17	.17
+n	-p	-p	4	3.63	246	2.46
-n	-p	-p	14	12.73	1356	13.56
+p	+n	-p	0	0	0	0

Table 10

RAD	NOR	EAS	REC	PREC	SIM	PSIM
-p	+n	-p	0	0	0	0
+n	+n	-p	0	0	0	0
-n	+n	-p	1	.91	236	2.36
+p	-n	-p	0	0	0	0
-p	-n	-p	1	.91	5	.05
+n	-n	-p	0	0	23	.23
-n	-n	-p	6	5.45	479	4.79
+p	+p	+n	0	0	0	0
-p	+p	+n	0	0	0	0
+n	+p	+n	0	0	0	0
-n	+p	+n	0	0	0	0
+p	-p	+n	0	0	106	1.06
-p	-p	+n	0	0	36	.36
+n	-p	+n	0	0	3	.03
-n	-p	+n	0	0	0	0
+p	+n	+n	1	.91	12	.12
-p	+n	+n	0	0	0	0
+n	+n	+n	0	0	0	0
-n	+n	+n	0	0	0	0
+p	-n	+n	22	20.00	1711	17.11
-p	-n	+n	4	3.63	584	5.84
+n	-n	+n	0	0	21	.21
-n	-n	+n	0	0	5	.05
+p	+p	-n	0	0	0	0
-p	+p	-n	0	0	0	0
+n	+p	-n	0	0	19	.19

Table 10 (Continued)

RAD	NOR	EAS	REC	PREC	SIM	PSIM
-n	+p	-n	0	0	0	0
+p	-p	-n	0	0	13	.13
-p	-p	-n	0	0	14	.14
+n	-p	-n	19	17.27	1617	16.17
-n	-p	-n	8	7.27	579	5.79
+p	+n	-n	0	0	0	0
-p	+n	-n	0	0	0	0
+n	+n	-n	0	0	0	0
-n	+n	-n	0	0	0	0
+p	-n	-n	0	0	1	.01
-p	-n	-n	0	0	0	0
+n	-n	-n	1	.91	97	.97
-n	-n	-n	1	.91	69	.69

Table 10 (Continued)

IV. DISCUSSION OF RESULTS AND CONCLUSIONS

The occurrence of earthquakes, at the larger sample sizes, was rejected as a uniform distribution with respect to the lunar periods, in all cases except one (Table 8). On certain days within the time frames of SFBAD-I and SFBAD-II, a larger number of earthquakes occurred relative to other days in these time periods. This "swarming" effect of numerous earthquakes occurring within hours and minutes of each other may indicate the lack of independence between the events. The "swarming" effect could also indicate that earthquakes do occur in a non-uniform manner. In order to decrease the dependence between the events, if the dependence does exist, the data were analyzed according to the magnitudes of the earthquakes. This method eliminated the "swarming" effect. An example of the "swarming" effect was on June 10, 1969, when 15 earthquakes occurred. When magnitudes greater than or equal to 2.0 were examined, the number of earthquakes which occurred on June 10, 1969, was reduced to five. The null hypothesis was still rejected for the three lunar periods. The fact remains that the null hypothesis was rejected in all cases but one at the larger sample sizes.

It is interesting to compare the polar plots of the Synodic Lunar Periods of the SFVD and the SFBAD-II. The largest percentage of earthquakes occurred, in both cases, in the first interval, or at the time of the new moon.

Also, the time periods of the two sets of data were similar. However, the polar plot of the SFBAD-I was not similar, but neither was the time period.

The occurrence of earthquakes with respect to the Draconic Lunar Period in the SFBAD-I and SFBAD-II are not the same. When analyzing the SFBAD-I, the null hypothesis was rejected at all magnitudes, but in analyzing the SFBAD-II the null hypothesis was accepted at all magnitudes.

The occurrence of earthquakes with respect to the Anomalistic Month in the SFBAD-I and SFBAD-II are similar to each other. The rejection of the null hypothesis at the one per cent significance level was the same for the larger sample sizes.

The null hypothesis was rejected when analyzing the SFVD with respect to the Synodic Lunar Period at the one per cent significance level when using the Chi-Square Test but was accepted using the Vn Test (Both tests would have rejected the null hypothesis at the 2.5 per cent significance level). The rejection was due mainly to the occurrence of 17 of the 110 earthquakes near the time of the new moon. In comparing these 17 earthquakes with respect to the combinations of the three components of the tidal force (as discussed in Section III), nothing of interest seems to be revealed. Four of the 17 earthquakes had the same combination but the four also occurred on the same day. The remaining 13 earthquakes had different combinations.

The acceptance in Section III, that the distributions of the 110 actual earthquakes and the 10,000 simulated earthquakes were the same seemed quite significant. Further analysis into why earthquakes never occur with certain combinations and why large numbers of earthquakes occur with other combinations may prove or disprove that the tidal force can trigger earthquakes.

V. THE COMPUTER PROGRAM

The time (GMT) of each origin of the lunar periods was read into the computer by the year (NA), the month (NB), the day (NC), the hour (ND), the minute (NE), and the second (SE). As discussed in Section II, the time of each origin was converted [Ref. 14] to the corresponding Julian Date (ORGP(I,J)).

The time (GMT) of each earthquake was read into the computer by the year (MA), the month (MB), the day (MC), the hour (MD), the minute (ME), and the second (SE). As discussed in Section II, the time of each earthquake was converted [Ref. 14] to the corresponding Julian Date (JDGMT(I)). Subsequently each of the JDGMT(I) was converted to the residual (RESD(I,J)) for each lunar period.

The following list defines the terms used in the Lunar Period Computer Program:

NBOX	The number of equal intervals on the interval (0,1).
ORGP(1,I)	The origin of the I^{th} Synodic Month.
ORGP(2,I)	The origin of the I^{th} Draconic Month.
ORGP(3,I)	The origin of the I^{th} Anomalistic Month.
PER(1,I)	The period of the I^{th} Synodic Month.
PER(2,I)	The period of the I^{th} Draconic Month.
PER(3,I)	The period of the I^{th} Anomalistic Month.
JDAY	Subroutine to convert year, month and day to the Julian Day Number [Ref. 14].

BEG(1)	The first origin of the Synodic Month to occur within the time frame of the data.
BEG(2)	The first origin of the Draconic Month to occur within the time frame of the data.
BEG(3)	The first origin of the Anomalistic Month to occur within the time frame of the data.
EN(1)	The last origin of the Synodic Month to occur within the time frame of the data.
EN(2)	The last origin of the Draconic Month to occur within the time frame of the data.
EN(3)	The last origin of the Anomalistic Month to occur within the time frame of the data.
JDGMT	The Julian Date each earthquake occurred.
JDLP	The time which each earthquake occurred within the period.
RES	The residual computed for each earthquake and placed on the unit circle.
NCNT	The number of occurrences within each subinterval.
NPTS	The total number of earthquakes.
EXVAL	The expected number of earthquakes within each subinterval.
PCT	The percentage of the number of occurrences within each subinterval.
CHISQ	The Chi-Square statistic.
SHELL	Subroutine to sort the residuals in ascending order [Ref. 2].

DIFF	The Vn statistic.
ROOTS	The Vn statistic times $\sqrt{N}$.

```
      REAL*8 FRACT,JDGMT,JDLP,RES,PER,PERP,ORG,ORGP
      DIMENSION PER(5),ORG(5),JDLP(5),NCNT(30,5),RESD(160,5)
      DIMENSION CHISQ(5),SUM(5),EMIN(5),EMAX(5),DIFF(5)
      DIMENSION ROOTS(5),ORD(161)
      DIMENSION ORGP(3,10),PERP(3,9),PCT(30,5),EXVAL(5)
      DIMENSION NUM(5),JDGMT(160),BEG(3),EN(3), ENPTS(5)
      DATA CHISQ/5*0.0/,SUM/5*0.0/
      DATA NUM/5*0/
      READ(5,0001) NBOX
 0001 FORMAT(I4)
      BOX=NBOX
      WRITE(6,7000) NBOX
 7000 FORMAT('1',/,42X,'UNIFORM ?',I5,' BOXES',/)
C***********************************************************************
C
C         CONVERT ORIGIN GREGORIAN DATES TO JULIAN DATES
C
C***********************************************************************
      DO 6000 I=1,3
      DO 6005 J=1,10
      READ(5,6999) NA,NB,NC,ND,NE,SE
 6999 FORMAT(1X,I4,I3,I3,I4,I3,F6.2)
      CALL JDAY(NC,NB,NA,JD)
      ORGP(I,J)=JD+(FLOAT(ND)+FLOAT(NE)/60.0+SE/3600.0)/24.0
      ORGP(I,J)=ORGP(I,J)-0.50
 6005 CONTINUE
 6000 CONTINUE
      BEG(1)=ORGP(1,2)
      BEG(2)=ORGP(2,2)
      BEG(3)=ORGP(3,2)
      EN(1)=ORGP(1,3)
      EN(2)=ORGP(2,9)
      EN(3)=ORGP(3,9)
      ORG(4)=ORGP(2,1)
      ORG(5)=ORGP(2,1)
      DO 6015 I=1,3
      READ(5,6995) (PERP(I,J),J=1,9)
 6995 FORMAT(10F8.5)
 6015 CONTINUE
      PER(4)=27.32166
      PER(5)=27.32158
      NPTS=0
      DO 0030 I=1,NBOX
      DO 0040 J=1,5
      NCNT(I,J)=0
 0040 CONTINUE
 0030 CONTINUE
      DO 0035 I=1,160
      DO 0045 J=1,5
      RESD(I,J)=0.0
 0045 CONTINUE
 0035 CONTINUE
      II=1
 0005 READ(5,1500,END=0020) MA,MB,MC,MD,ME,SE
 1500 FORMAT(1X,I4,I3,I3,I4,I3,F6.2)
      IF(MA.EQ.0) GO TO 0020
C***********************************************************************
C
C         CONVERT EARTHQUAKE GREGORIAN DATES TO JULIAN DATES
C
C***********************************************************************
      CALL JDAY(MC,MB,MA,JD)
      NPTS=NPTS+1
      FRACT=(FLOAT(MD)+FLOAT(ME)/60.0+SE/3600.0)/24.0
      JDGMT(NPTS)=JD+FRACT-0.500
      GO TO 0005
 0020 DO 4000 I=1,5
      DO 4005 L=1,NPTS
      IF(I.GT.3) GO TO 4100
      IF(JDGMT(L).LT.BEG(I)) GO TO 4005
      IF(JDGMT(L).GT.EN(I)) GO TO 4005
      DO 6030 J=2,10
```

```
      IF(JDGMT(L).GT.ORGP(I,J)) GO TO 6030
      ORG(I)=ORGP(I,J-1)
      PER(I)=PERP(I,J-1)
      J=10
 6030 CONTINUE
 4100 NUM(I)=NUM(I)+1
      JDLP(I)=JDGMT(L)-ORG(I)
C***********************************************************************
C
C         COMPUTE RESIDUALS
C
C***********************************************************************
      RES=DMOD(JDLP(I),PER(I))/PER(I)
      IF(RES.LT.0.D0) RES=RES+1.D0
C***********************************************************************
C
C         PLACE RESIDUALS INTO 20 BOXES ON INTERVAL (0,1)
C                      FOR EACH LUNAR PERIOD
C
C***********************************************************************
      INDEX=RES*BOX+1.0
      NCNT(INDEX,I)=NCNT(INDEX,I)+1
      RESD(II,I)=RES
      II=II+1
 4005 CONTINUE
      ENPTS(I)=NUM(I)
      EXVAL(I)=ENPTS(I)/BOX
      DO 0070 J=1,NBOX
      PCT(J,I)=FLOAT(NCNT(J,I))/ENPTS(I)
 0070 CONTINUE
C***********************************************************************
C
C         COMPUTE CHI-SQUARE ON BOXES
C
C***********************************************************************
      DO 0098 J=1,NBOX
      SUM(I)=(FLOAT(NCNT(J,I))-EXVAL(I))**2/EXVAL(I)
      CHISQ(I)=CHISQ(I)+SUM(I)
 0098 CONTINUE
C***********************************************************************
C
C         SORT RESIDUALS
C
C***********************************************************************
      CALL SHELL(NUM(I),RESD(1,I))
      NO=NUM(I)
      DO 0033 J=1,NO
      ORD(J)=FLOAT(J-1)/ENPTS(I)
 0033 CONTINUE
      ORD(NUM(I)+1)=1.0
      EMIN(I)=0.0
      EMAX(I)=0.0
C***********************************************************************
C
C         COMPUTE MODIFIED K-S TEST ON THE LUNAR PERIODS
C
C***********************************************************************
      DO 0054 J=1,NO
      RESDX=RESD(J,I)
      EMAX(I)=AMAX1(RESDX-ORD(J),EMAX(I))
      EMIN(I)=AMIN1(RESDX-ORD(J+1),EMIN(I))
 0054 CONTINUE
      DIFF(I)=EMAX(I)-EMIN(I)
      ROOTS(I)=DIFF(I)*SQRT(ENPTS(I))
      II=1
 4000 CONTINUE
C***********************************************************************
C
C         TABULATE THE RESULTS
C
C***********************************************************************
      WRITE(6,9999)
```

```
9999 FORMAT(9X,'SYNODIC MONTH',5X,'DRACONIC MONTH',5X,
    1'ANOMALISTIC MONTH',5X,'SIDEREAL MONTH',5X,
    2'TROPICAL MONTH',//)
     DO 0060 I=1,NBOX
     WRITE(6,9900)(NCNT(I,J),J=1,5)
9900 FORMAT(15X,I4,15X,I4,18X,I4,15X,I4,15X,I4)
0060 CONTINUE
     WRITE(6,4999)(NUM(J),J=1,5)
4999 FORMAT(/,11X,I4,' QUAKES',8X,I4,' QUAKES',11X,I4,
    1' QUAKES',8X,I4,' QUAKES',8X,I4,' QUAKES',/)
     WRITE(6,7005)
7005 FORMAT(//,46X,'PERCENTAGES',/)
     WRITE(6,9999)
     DO 0155 I=1,NBOX
     WRITE(6,8100)(PCT(I,J),J=1,5)
8100 FORMAT(11X,F7.3,12X,F7.3,12X,F7.3,15X,F7.3,12X,F7.3)
0155 CONTINUE
     WRITE(6,2044)
2044 FORMAT('1',//,45X,'CHI-SQUARE TEST',/)
     WRITE(6,9999)
     WRITE(6,8200)(CHISQ(J),J=1,5)
8200 FORMAT(11X,F7.3,12X,F7.3,12X,F7.3,15X,F7.3,12X,
    1F7.3,//////////)
     WRITE(6,9999)
     WRITE(6,4988)(NUM(J),J=1,5)
4988 FORMAT(2X,9X,I4,' QUAKES',8X,I4,' QUAKES',11X,I4,
    1' QUAKES',8X,I4,' QUAKES',8X,I4,' QUAKES',//)
     WRITE(6,2022)(DIFF(J),J=1,5)
2022 FORMAT(1X,'MODIFIED',/,3X,'K-S',3X,F9.5,10X,F9.5,10X,
    1F9.5,13X,F9.5,10X,F9.5,/,1X,'STATISTIC',//)
     WRITE(6,2033)(ROOTS(J),J=1,5)
2033 FORMAT(2X,'ABOVE',/,1X,'STATISTIC',/,2X,'TIMES',2X,
    1F9.5,10X,F9.5,10X,F9.5,13X,F9.5,10X,F9.5,/,1X,
    2'ROOT(NPTS)')
     STOP
     END


     SUBROUTINE JDAY(D,M,Y,J)
     INTEGER*4 D,Y,YA,C
     IF(M.GT.2) GO TO 0055
     IM=M+9
     IY=Y-1
     GO TO 0065
0055 IM=M-3
     IY=Y
0065 C=IY/100
     YA=IY-100*C
     J=(146097*C)/4+(1461*YA)/4+(153*IM+2)/5+D+1721119
     RETURN
     END


     SUBROUTINE SHELL(N,X)
     DIMENSION X(1)
     M=N
0101 M=M/2
     IF(M.EQ.0) RETURN
     K=N-M
     J=1
0111 I=J
0121 IM=I+M
     IF(X(I).LE.X(IM)) GO TO 0131
     S=X(I)
     X(I)=X(IM)
     X(IM)=S
     I=I-M
     IF(I.GE.1) GO TO 0121
0131 J=J+1
     IF(J.LE.K) GO TO 0111
     GO TO 0101
     END
```

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An Analysis of Earthquake Data with Respect to the Tidal Force

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ABSTRACT

Earthquake data from California from the period of January 1, 1969, to December 31, 1971, has been analyzed by two methods. The first method compares the occurrence of earthquakes with the Synodic, Draconic and Anomalistic Lunar Periods. Statistical tests to determine if the earthquakes are uniformly distributed over each of the three lunar periods are presented. The second method compares three components of the tidal force vector and their derivatives at the times of earthquake occurrences.

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